DCIEM SL1999-c

RTO-MP-20
AC/323(HFM)TP/7

RTO-MP-20

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION
BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO MEETING PROCEEDINGS 20

Models for Aircrew Safety Assessment: Uses, Limitations and Requirements

(la Modélisation des conditions de sécurité des équipages : applications, limitations et cahiers des charges)

Papers presented at the Specialists' Meeting of the RTO Human Factors and Medicine Panel (HFM) held at Wright-Patterson Air Force Base, Ohio, USA, 26-28 October 1998.

TECHNICAL EVALUATION REPORT

by

Jack P. Landolt, PhD
Defence and Civil Institute of Environmental Medicine
Toronto, Ontario, Canada M3M 3B9

and

Ints Kaleps, PhD
Louise A. Obergefell, PhD
Human Effectiveness Directorate
Air Force Research Laboratory
Wright-Patterson Air Force Base
Ohio 45433-7947, U.S.A.

1. INTRODUCTION

The Human Factors and Medicine (HFM) Panel of the NATO Research & Technology Organization (RTO) held a Specialists' Meeting on "Models for Aircrew Safety Assessment: Uses, Limitations and Requirements" at the Hope Hotel and Conference Center, Wright-Patterson Air Force Base (WPAFB) (near Dayton, Ohio), USA, 26 - 28 October 1998. The Meeting was held to address a topic of importance to the Panel, and to honour Dr Henning E. von Gierke, Director Emeritus, Human Effectiveness Directorate (HE), Air Force Research Laboratory (AFRL), WPAFB for his pioneering work in biodynamics and his extensive service to NATO/AGARD,* the antecedent organization to RTO addressing issues in aerospace research and development. Thirty-five papers, including three keynote addresses, were given from the NATO countries of Canada, The Netherlands, United Kingdom, and United States. These are included in this Meeting Proceedings, as is a paper by Mr James W. Brinkley, Director, AFRL/HE paying tribute to Dr von Gierke. There were 70 registrants for the Meeting including representatives from the NATO Partnership-for-Peace countries Lithuania and Poland, and Japan.

2. THEME

Significant advances have been made in modelling human physical and physiological responses to extreme environments. Additionally, technological advances in computer speed and power have made modelling a feasible research and design tool. The military and civilian aviation and land-vehicle communities are using computer simulations extensively to predict human physical and physiological responses, to reduce testing requirements, to rapidly design improved protective systems, and to perform human safety- systems analyses. These models are revolutionizing the way physiologists, mathematicians, and engineers assess aircrew safety. Furthermore, appropriately-validated models will render the collection of volunteer human and animal test data less and less necessary in the future.

3. PURPOSE AND SCOPE

The purpose of this Specialists' Meeting was to review a variety of models that will address current and future issues in aerospace physiology and aircrew safety.

The scope was broad covering the modelling of human responses to impact, emergency escape, sustained acceleration, mechanical shock, vibration, motion sickness, high altitude, blast, extreme thermal conditions, directed energy, live fire, and other hazardous conditions. A variety of models were considered, including lumped-parameter, rigid-body, finite-element, statistical, physiological, and empirical models. The models described the human body response to environmental stressors, and the systems with which the body interacts. Also considered were the databases and tolerance criteria used with these models. Special presentations - the keynote addresses - focussed on the validations, limitations, and appropriate applications of different models.

The participants included military and civilian experts in mathematical and computer modelling, biomechanics, biomedical and other engineering disciplines, radiology, physiology and other life sciences, physics, and human factors. Presentations were invited from industry, defence

* AGARD is the acronym for Advisory Group for Aerospace Research and Development

and other governmental research laboratories, universities, and health care centres.

4. SYMPOSIUM PROGRAM

Each day, the technical programme commenced with a keynote address that discussed in general terms different aspects of models, and criteria development and usage. These presentations were:

a. Keynote Address 1 - Physical Models: The Good, The Bad, The Ugly, by Dr Charles Hatsell, Biodynamic Research Corporation, San Antonio, TX, US;

b. Keynote Address 2 - Injury Measurements and Criteria, by Dr Kennerly H. Digges, National Crash Analysis Center, The George Washington University, Ashburn, VA, US; and

c. Keynote Address 3 - Model Validation, by Dr Ints Kaleps, AFRL/HE, OH, US.

The remaining papers were arranged in six Sessions as follows:

a. Session I - Modelling Human Responses to Impact and Ejection Accelerations
Chairmen: Dr J.S.H.M. Wismans, NE and Dr L.A. Obergefell, US

Seven papers described quantitative databases, and mathematical and physical models of human responses to impact and ejection.

b. Session II - Modelling Human-Systems Interaction during Ejection and Impact
Chairmen: Dr L.A. Obergefell, US and Dr J.S.H.M. Wismans, NE

Six papers addressed the issue of modelling human-systems interaction during escape and impact conditions.

c. Session III - Sustained Gz Acceleration: Cardiovascular and Cerebrovascular Response Modelling
Chairmen: Dr R.R. Burton, US and Mr W.D. Fraser, CA

Four papers discussed the subject of modelling systemic system responses to Gz.

d. Session IV - Sustained Gz Acceleration: Modelling Human Responses to Anti-Gz Protection Strategies
Chairmen: Mr W.D. Fraser, CA and Dr R.R. Burton, US

Five papers were given on modelling responses to anti-G suits, positive pressure breathing (PBG), and anti-G straining maneuvres.

e. Session V - Modelling Human Responses to Other Adverse Flight Environments
Chairmen: Dr J.P. Landolt, CA and Dr I. Kaleps, US
Papers on modelling responses to mechanical shock, vibration, motion sickness, and altitude decompression sickness (DCS) were given.

f. Session VI - Modelling Human Responses to Harsh Conditions in Air Environments
Chairmen: Dr I. Kaleps, US and Dr J.P. Landolt, CA

One paper described a new joint US Army, Navy, and Air Force model – Operational Requirement-based Casualty Assessment (ORCA) - that assesses the impact of trauma on performance; two others discussed sub-models for predicting injury that port into ORCA. The remaining three papers dealt with modelling the bioeffects of directed energy exposure, skin burns, and blast overpressure.

Additionally, there was a half-day technical tour of relevant biodynamic, bioacoustic and alternative-control-technology facilities at the AFRL/HE.

5. TECHNICAL EVALUATION

5.1 Keynote Addresses

Keynote Address 1 considered the different physical models in terms of their being good, bad or 'ugly'. Good models make predictions that are close to experimental measurements and provide important information regarding a process or system. Models are bad if they fail to account for all of the physical phenomena required to describe an outcome. So-called ugly models may not be technically incorrect, but they fail to provide any insight into a process or about a system.

In addition to their predictive and explanatory capabilities, good physical models also differ from bad models in that they are:

- simple in that they require the least number of equations, lines of software, or components necessary to provide a convincing answer,
- clear in that they can be understood and used by any knowlegeable person familiar with the problem,
- objective in that they are independent of human bias, and
- tractable in that the cost of carrying out the computation is affordable

(Casti, J.L. Would-be Worlds. New York: Wiley, 1997).

Keynote Address 2 discussed the types of injury measurements obtained from frontal- and side-impact dummies, and the associated injury criteria that have been specified by the US Department of Transportation in safety

standards from crash testing of motor vehicles incorporating these dummies. Injury criteria based on frontal-impact dummies concern measurements of head and chest accelerations, neck and lower legs forces and moments, chest deflections, and femur loads. Measurements for criteria from side-impact dummies are confined to accelerations of the ribs, spine, and pelvis. Criteria based on these measurements are set so that the risk of serious injury is no more than 30%. In general, injury criteria for frontal impacts are well established but still evolving; those of side impacts require considerable refinement and much more research.

Keynote Address 3 addressed the issue of validating predictive models, i.e., models that are based on fundamental mechanisms for which response properties can be measured. The level of validation considered is dependent on the ultimate application of the model. Applications may involve:

- better insight into physical phenomena,
- reconstruction of physical events,
- use as a design tool, and
- systems simulation.

Considerations in model design to facilitate model validation include:

- model complexity, e.g., degrees of freedom,
- completeness of representation,
- accuracy of observation of model variables, and
- range of validity.

Model credibility is dependent on two separate and distinct tests:

- verification process which establishes that a model (or simulation) accurately depicts what the designer intended and that the requirements are correctly implemented in software, and
- validation process which compares the degree to which a model (or simulation) represents the real world.

Full credibility is achieved only when both tests are taken into consideration.

In validating a model, the motto should be: keep it simple, but accurate. Only the relevant response characteristics should be considered. For example, only the essential degrees of freedom, variables that can be measured, and parameters that can be obtained from direct measurements should be used. Ambiguity and unnecessary complexity will do much to undermine model validity and acceptance.

5.2 Modelling Human Responses to Impact and Ejection Accelerations

Modelling and simulation are becoming increasingly important operations in the conception, design, research, development, test and evaluation of crashworthy seats, restraints, and escape systems. Critical to the success of these operations is the readily-available, massive amounts of biodynamic data that have been collected from volunteer human and animal testing for the past 30 years. These data have provided the design basis for anthropomorphic human analogues - computer models and mechanical dummies - that are used widely today for assessing body response and injury risk to mechanical forces.

Perhaps, it is fitting that this Specialists' Meeting should start off with a paper that discusses a topic that is central to Dr von Gierke's concerns (Buhrman (1)). It was at a symposium in 1977 that he proposed the notion of a national (US) biodynamics data bank (Aviat. Space Environ. Med. 49(1): 347, 1978). More specifically, Dr von Gierke stated that: *"... it appears essential that the material properties and mechanical characteristics fed into the mathematical models be based on all the relevant data available, and not on a few test results from an individual investigator. In view of the time, cost, and risk involved in obtaining this broad spectrum of experimental data, I think consideration should be given to the establishment of some kind of centralized data bank that would store: a) directly measured mechanical properties of human tissue, b) mechanical properties of tissues of animals most frequently used in biodynamic research, c) human injury/rupture information derived from accident analysis, d) human tissue/organ response characteristics derived from volunteer biodynamic tests, e) human body dynamic response data from volunteer tests, and f) animal body subcritical and critical response data. This data bank should be fed by all laboratories working in this field and its data should be generally available. In this way, model parameters and inputs could be compared to the best and, above all, to all types of response data available."*

Such a national biodynamics data bank never materialized. Buhrman's paper, however, provides an overview of the current status regarding the evolution and contents of the Biodynamics Data Bank (BDB) that was initiated in 1984 at WPAFB for the development and validation of impact simulation and injury models.

The BDB includes acceleration, force and motion data from a large number of tests conducted on man-rated facilities at WPAFB, including those from both horizontal and vertical motion devices. Such information as the time histories and peak biodynamic responses from impact tests, anthropometric measurements from test subjects, and bibliographic information from relevant references are included in the BDB. These data and pertinent summary information from past biodynamic test programs reside in the BDB through a Windows NT® server which will allow users elsewhere to seamlessly access information according to their own requirements. A test index enables the

accessing of all impact test parameters, including type of test facility, data acquisition system, seat fixture, restraint system, helmet, gender anthropometry, and input acceleration profile. Currently, the slow-motion videos, photographs and pertinent printed material from the impact tests are being digitized for future entry into the BDB.

Using quantitative computed tomography, Diccucio et al. (2) are collecting data from vertebral bones of anthropometrically-similar males and females. The vertebral geometry, bone density, end-plate cortical bone thickness, and trabecular bone architecture of a number of spinal vertebrae are being examined. Gender differences in these parameters may help explain differences in vertebral load bearing capacities. The authors intend to use the ensuing results in a multivariant regression equation that would predict vertebral injury risk during impact or ejection. Only preliminary results are given in their paper. Indications are that mean trabecular bone mineral densities in C2 and C5 vertebrae are significantly higher in females than in males. A gender comparison indicated that only the end-plate cross-sectional area in the L4 vertebrate was significantly higher in males; trabecular bone mineral density, area x bone mineral density, and predicted compressive strength were not statistically significantly different.

Neck loading from wearing helmet-mounted displays and night-vision goggles increases the chance of neck injury during ejection. To better understand the mechanisms involved and define the criteria for allowable helmet mass properties, Ziejewski and colleagues (3) studied the modes of head-neck response in females to vertical impacts. Acceleration levels (10 G peak) comparable to those experienced in the catapult phase of ACESII seat ejections were used. The helmet mass properties were varied to simulate those in current helmet-mounted systems. Five modes of head-neck response were identified: two representing forward neck and head rotation, two representing forward neck rotation and rearward head rotation, and one representing no significant neck or head rotation. Two experimental measurements, the initial linear (forward head) acceleration at the mouthpiece and the (head) pitch of the mouthpiece relative to a shoulder marker, uniquely defined the head-neck response. Other factors such as initial head-neck position, anthropometry, helmet type, its mass and centre of gravity, and acceleration level should also be investigated for their contributions in defining the modes of response.

Bomar and Pancratz (4) commenced their presentation with a historical overview of a head-spine model, developed by the USAF in the late 1970s, that found limited application because of the intractability of the code in which it was written. The US AFRL has had the model re-coded and improved for solution on a Personal Computer under a Windows® environment. The model is comprised of six types of elements as follows:

- rigid bodies representing the head, spine, pelvis, rib cage and viscera having mass properties and capable of six degrees of freedom in motion;
- springs to represent ligaments, vertebral articular facets and abdominal visceral elements, that produce a cubic force to strain and a damping force to rate of strain;
- cervical muscles that produce a force proportional to strain and the concentration of an 'activator molecule' governing muscle behaviour;
- hydrodynamic elements employing fluid-filled pentahedrons for modelling the articular facets;
- beams having two end-plates for modelling intervertebral discs attached to adjacent vertebrae or ribs; and
- environmental elements consisting of springs as restraints, elastic planes as contact surfaces, and motion constraints.

The authors described the numerical methods employed for solving the underlying equations of motion. They raised concerns regarding validation of all complex multi-body biomechanical models. One application of the model is for simulating spinal loads resulting from ejection-seat accelerations. To a question from the audience regarding choice of mathematical models, Bomar noted that their head-spine model estimates the internal forces and motions within the human at the anatomic level, whereas surrogates such as the MAthematical DYnamic MOdel (MADYMO) and Articulated Total Body (ATB) programs can simulate gross effects only.

(Details on the mathematical dummies MADYMO and ATB, and (see below) the mechanical dummies Hybrid II and Hybrid III, THOR (TAD-50M), and EUROSID-1 are given in AGARD-AR-330: Anthropomorphic Dummies for Crash and Escape System Testing.)

Meeting neck biofidelity performance requirements in current motor vehicle safety standards for frontal impacts is achieved by using the Hybrid III dummy in crash testing. The Hybrid III neck is used also in dummies for aerospace applications. Wismans et al. (5) reported on work conducted at TNO Road-Vehicles Research Institute, The Netherlands, that compared neck performance of the Hybrid III with that of the new frontal impact dummy, THOR, and a neck model developed for incorporation in MADYMO. The authors demonstrated that the neck of the new THOR dummy, which was developed by GESAC as an improved dummy for the US National Highway Traffic Safety Administration, was more biofidelic than the Hybrid III neck. Moreover, the mathematical neck model in

MADYMO, which incorporated cervical vertebrae, ligaments, and active neck musculature, was even more representative of human responses during frontal impacts than the mechanical neck models. Interestingly, the authors showed that acceleration-based responses from dummy sensors are poor discriminators of neck biofidelity.

In order to improve seats and other safety components, the military and the aviation industry require a better understanding of occupant reaction to vertical crash conditions. The Hybrid II and Hybrid III anthropomorphic test dummies have been designed and used extensively for analyzing motion kinematics and injury potential in frontal-impact automotive crashes. Manning and Happee 6) collected militarily-relevant, drop test data from 50th-percentile Hybrid II and Hybrid III male dummies secured by five-point harnesses to UH-60 (Black Hawk) helicopter crew seats. Results from the tests were incorporated into a MADYMO program that simulated the Hybrid dummies. Comparisons were made between the mechanical and mathematical dummies of acceleration data from the head, chest and pelvis; neck and lumbar loads and moments; and shoulder belt and lap belt loads. After accounting for any data acquisition errors that may have been introduced during the tests, the results showed a good correlation for acceleration and compressive loading. Some differences were noted for the lumbar shear force and bending moment, and the belt loads. The authors concluded that the MADYMO Hybrid model provided an effective tool for evaluating vertical crash conditions.

Pellettiere and colleagues (7) developed a finite-element model of the forearm of a 5th-percentile female for the purpose of assessing bone strength. The geometry of the model was based on computed tomographic scans of the radius and ulna bones. Subsequently, a transversely-isotropic material model, developed at the University of Virginia to provide the proper mechanical response of bone, was applied to the geometric model. This combination was then incorporated into an LS-DYNA3D, finite-element computer program. Simulations using the model for predicting bone behaviour during impact compared favourably to experimental test responses. This model should find application in a range of simulations including those for predicting injury in arm-airbag interactions. Additional drop-test results obtained from cadavers - 55-60 years of age - demonstrated dynamic bending strengths of 128 Nm for the humerus, and 58 Nm for the forearm of the 5th-percentile female. It was suggested by the authors that these results could be used as injury criteria in airbag studies.

5.3 Modelling Human-Systems Interaction during Ejection and Impact

Increasingly, multi-body and finite-element models are being used to represent human-systems interaction in crash and escape-system simulations. Multi-body (rigid bodies connected by joints) models are particularly useful for simulating the spatial dynamics and interactions of complex kinematical structures such as the human body with mechanical systems such as vehicle interiors or ejection seats. Finite-element models allow for the study of local stresses and strains during impact; however, in many instances, validated databases of structural and material properties of body components are not available yet. As these models improve, and databases are validated and standardized, simulations will become more realistic thereby reducing the need for human subject testing to assess aircrew safety to impact.

Obergefell and colleagues (8) described the use of biodynamic modelling in the AFRL for resolving different military equipment and personnel safety issues. In short, validated models are used to provide rapid evaluations when other test methods are too expensive or unfeasible. The ATB model, a multi-body occupant model, is used extensively to determine crew motion and contact with equipment and surfaces during systems design and test procedures. Here, modelling is used to evaluate human-systems interactions, to develop safe design criteria, and to predict crew response to test situations. Moreover, when unusual test results are given in employing new dummies, biodynamic modelling is applied to sort out discrepancies and to extend test measurement capabilities. Simulations of tests are also used to determine which equipment modifications will likely improve conditions or to narrow future test requirements. The ATB model is constantly updated from, and validated against, human and dummy impact-test results of realistic military applications.

Ma and colleagues (9) described recent model developments for assessing ejection-seat motion, occupant biodynamic response and seat-occupant separation. An ejection-seat model, EASY5/ACESII, was coupled with the ATB model, to simulate the dynamic interaction between the seat and human being during the early phases of the ejection process. The two models interacted synergistically. Wind tunnel data from the EASY5/ACESII model were used to provide the total aerodynamic forces on the occupant in the ejection seat. Then the ATB model calculated the component forces and torques on the individual segments of the seat occupant. When these components were subtracted from the total forces and torques, the force components acting directly on the seat were obtained. When an occupant-seat separation signal was generated in the EASY5/ACESII model to initiate restraint-harness release, it was immediately transferred to the ATB model, and the appropriate aerodynamic forces and torques were then applied only to the separated occupant. At the same time, the recovery parachute force from the EASY5/ACESII model was sent to the ATB

model, where the combined forces from gravity, recovery parachute, and aerodynamics separated the occupant from the ejection seat. Test validation studies demonstrated the utility of the model in successfully predicting the main features of ejection-seat motion and occupant dynamic response.

Ejection from the next generation of high-speed aircraft may significantly increase the risk of head/neck injury from windblast. Chan, Yu and Stuhmiller (10) provided details on the use of wind/water tunnel and sled test data, and biomechanical modelling for determining head protection against windblast in aircrew during seat ejections. Results indicated that the windblast load on the head interacts strongly with the inertial dynamics of an ejection-seat/test-dummy combination during aircrew escape. Inertially, yaw conditions, in addition to adding a significant load to the side of the head, continuously increased the lift forces on the head. Various protective 'wind flow stagnation' strategies were tested and modelled. Some subjected the head to unwanted oscillations; others significantly increased the head side forces. Test results and simulations employing computational fluid dynamics showed that a protective strategy using an 'open-brim' concept would reduce the lift forces and provide for smaller side-force increases. This paper clearly demonstrated the power of using combinations of tests, simulations and analyses for developing protective strategies in complex human-systems interactions.

High-power computer modelling employing finite-element analysis is being used extensively for evaluating and improving the protective environment in hazardous situations. Digges and Bedewi (11) have indicated that finite-element modelling is the most advanced tool for simulating an impact or high-acceleration event. Advantages of the finite-element method for simulating human-vehicle interaction in a crash environment over other methods include:

- having advanced algorithms of contact surfaces for determining structural deformations;
- having good material models, such as those for fabrics, elasto-plastics, etc., for simulating different structures and assessing crash dynamics;
- the ability to apply dissimilar material properties to different elements in the model;
- the ability to collect a large variety of data, including those of stress, strain, displacement, velocity, acceleration, energy, etc. anywhere in the model; and
- not being restricted to limitations imposed by other means for investigating protective environments; e.g., the lack of total biofidelity in many modern test dummies inhibits total analysis in many instances.

Digges and Bedewi described a finite-element model of a vehicle occupant that is based on a validated computer representation of a Hybrid III test dummy. Components of the human such as the arms, legs, head/neck, etc. can be continuously upgraded in a biofidelic sense, and the changes made may then be transitioned back into the full-body dummy model. This gives a Hybrid III computer model that becomes more human-like as improvements are made. The authors cited the example of the development of an improved lower-limb model embodying muscle activation which, when incorporated in the Hybrid III computer model, enabled previously-missing injury mechanisms to be discovered. Applications for this model would include:

- the design of protective gear for preventing trauma in athletes;
- improved automobile crashworthiness for the prevention of occupant injuries during impact;
- improved military aircraft crashworthiness for pilot protection during escape and impact; and
- improved civil aircraft crashworthiness for civilian occupant protection during non-catastrophic airline emergencies.

In situations where the occupant is seated in an out-of-position orientation in a vehicle, the pattern of the airbag unfolding during deployment could be a critical safety issue. Avula, Kaleps and Mysore (12) used the finite-element model, LS-DYNA3D, to investigate fabric density, bag elasticity, input gas temperature and extent of venting during the evolution of an unfolding airbag impacting with a solid sphere. The influence of these parameters on the contact during impact was significant. Lowering the material density resulted in a higher velocity of the unfolding airbag, which increased the sphere rebound velocity. Lowering the fabric elasticity resulted in an increased contact time and a higher sphere rebound velocity. At low input gas temperature, the airbag volume remained low, contact time with the sphere was long, and the sphere had a very low rebound velocity. The acceleration and rebound velocity of the sphere were the highest when there was no venting and the least for maximal vent area. These results have important implications for designing optimal occupant safety systems in survivable crashes of fixed- and rotary-wing aircrafts. (Research on incorporating airbags in aircraft is being studied seriously by the aerospace industry. The use of airbags and other inflated restraint systems for head injury protection in aircraft crashes was the subject of Papers #21 & #22 in AGARD-CP-597: Impact Head Injury: Responses, Mechanisms, Tolerance, Treatment and Countermeasures.)

Issues relating to the US Federal Aviation Administration (FAA) regulations for occupant protection in transport aircraft are being addressed by industry and

government agencies. In this regard, the FAA has conducted tests using the automotive side-impact dummy, EUROSID-1, for assessing the potential for injury of side-facing sofas in aircraft. Assessed were the effects of thorax impact on an interior rigid wall with and without padding, body-to-body contact, and upper-torso restraint loads. Feulings and colleagues (13) have developed and validated a MADYMO computer model that predicted the test results quite well. In particular, both the model and the tests demonstrated the benefit of wall padding in reducing injury. The MADYMO simulations should enable the assessment of additional factors, such as occupant-size effects and restraint-system geometry, more cost effectively than would be the case with test sleds.

.4 Sustained Gz Acceleration: Cardiovascular nd Cerebrovascular Response Modelling

The loss of aircrew and aircraft through G-induced loss f consciousness (G-LOC) continuous to be a serious roblem for the NATO air forces. Further studies into the hysiological effects of this phenomenon are required. In rticular, good models need to be developed to better derstand human tolerance to acceleration. For example, cent work involving negative-to-positive Gz transitions - e so-called push-pull maneuvre - during high-rformance aircraft flights would indicate that, perhaps, man tolerance to acceleration may have been erestimated. This is supported by two recent papers hich suggest that the push-pull effect represents a gnificant source of G-LOC risk for accidents in high rformance aircraft in air combat training and during erational missions (Aviat. Space Environ. Med. 69(11): 83 & 1104, 1998). Four papers described models for ploring the effect of sustained Gz acceleration, including push-pull transition, on cardiovascular and ebrovascular performance.

Walsh, Cirovic and Fraser (14) described a thematical model of cardiovascular function to +Gz in ich physiological reflexes were neglected. A closed-loop cular network of uniform, flexible tube segments was d that incorporated lumped parameter models of the rt chambers. Valves were embedded in the segments resenting veins, and in the entrance and exit chambers the heart. The model had to incorporate at least one ve in the vena cava just below the heart; otherwise, the ulated blood would drain into the inferior systemic ns at physiologically-excessive speeds. Muscular ractions of the heart were simulated by a time-varying stance model. Segmental blood flow was described in ns of blood wave propagation by a pair of first-order ial differential equations. The equations were solved erically in a finite difference scheme. Results showed liac output decreasing and increasing, respectively, as increased and decreased. Central arterial pressure, the factor that governs the generation of G-LOC, did not follow physiological principles, accompanying instead the rise and fall of the cardiac output. Cardiac output returned to normal during high Gz when the lower body and abdomen were both protected through G-suit inflation. Protection was significantly reduced by lower body coverage alone.

The effect of high acceleration on the left ventricle is most severe when it is directed along the body z-axis. During some flight maneuvres, aircrew are subjected to +Gz levels as high as 10 G. In a previous communication at a NATO symposium, Tabarrok and colleagues described a three-dimensional, finite-element model of the left ventricle that was reconstructed from medical images of the human heart to study stress-strain relationships to such high accelerations (see Paper #20 in AGARD-CP-516). In the current paper, Behdinan, Tabarrok, and Fraser (15) have developed a new model of the left ventricle that is comprised of 3300 finite elements. Although a recent NATO/AGARD Working Group established that no pathologic cardiac changes were evident from a retrospective echocardiographic study of pilots repeatedly exposed to high, sustained Gz acceleration (AGARD-AR-351), investigations with this model may further confirm these results. Alternatively, the model may give new insights into the types of conditions required for inducing deleterious stress-strain in, and gross distortion of, the left ventricle that could jeopardize subsequent normal heart function in pilots flying high performance aircraft. In that regard, preliminary results with the model showed that, under high accelerations, the heart elongates and greater stresses are obtained at the aortic end of the heart than at the apex of the left ventricle.

A good knowledge of cerebral blood flow helps to understand the mechanisms subserving impaired vision or G-LOC during excessive exposure to Gz. Cirovic, Walsh and Fraser (16) designed a model which demonstrated that a G-induced reduction of blood flow to the brain is primarily caused by venous collapse resulting from an increased vascular resistance in the extracranial veins. Accordingly, detailed jugular veins were incorporated in the model. Cerebrospinal fluid prevents the intracranial vessels from collapsing during Gz so blood flow is preserved therein. Therefore, this model included simplified intracranial vessels, which were represented by a vascular resistance that was independent of Gz. The extracranial arteries were accounted for by introducing a hydrostatic pressure drop from the heart to the head. Autoregulation of cerebral vascular resistance to changing cerebral perfusion pressures also was incorporated. The jugular veins were modelled using one-dimensional equations of fluid dynamics and a nonlinear relation between transmural pressure and local vessel cross-sectional area was introduced. Gz was varied from -5 to

+10 G which encompasses the high-G environment of current high performance aircraft. The model reproduced the cerebral blood flow drop with increasing +Gz, while autoregulation was ineffective at higher +Gz because of the dominance of the extracranial venous resistance. The model predicted an increase in cerebral blood flow for elevations of central venous and arterial blood pressures. This was attributed to the fact that an elevated central venous pressure maintained extracranial venous patency by preventing venous collapse.

Paper #17 was to have described a model of the physiological mechanisms subserving cerebral ischemia during increasing +Gz. However, this paper was not presented.

Kapps and Fraser (18) used a combination of linear and nonlinear models to describe experimental physiological responses (eye-level blood pressure vs. Gz) for the push-pull effect. In experimental data, a sub-group of subjects had physiological responses that were highly nonlinear. The remaining responses could be described by a low-order, linear transfer function to both push-pull and +Gz maneuvres. Interindividual variations were pronounced in subjects demonstrating nonlinear behaviour. Additional data will be collected to validate these results.

5.5 Sustained Gz Acceleration: Modelling Human Responses to Anti-Gz Protection Strategies

Extended coverage anti-G suits combined with positive pressure breathing (PBG) have significantly enhanced the protection of aircrew to high +Gz (and high altitude). Current life-support systems, however, do not adequately protect aircrew during complex push-pull maneuvres. Morcover, they fail to adapt to physiological changes in aircrew during a mission; in part, this is due to the inability of protective systems to adapt to the body's blood pressure regulating system, the aortic and carotic bararecceptors (body-pressure sense organs). Current mathematical models of baroreceptor function do not allow for representation of the extreme changes in blood pressure and blood distribution that follows the application of very high +Gz. Neither do they address the extreme pressure shifts generated by the anti-G life-support equipment. Using the Caltech software package GENESIS (GEneral NEural SImulation System), Fraser (19) is developing hierarchical models of baroreceptor function that will include neuronal interaction within the baroregulation centres of the brain, the transient dynamics of pressure-induced stretch in the baroreceptors, the effects of local pressure gradients within the baroreceptors, and the dynamic response to Gz of each of these subsystems. These are relevant factors that affect the body's response to Gz and the efficacy of life- support equipment in preventing G-LOC. In the presentation at this Specialists' Meeting, only preliminary work was demonstrated.

Current pressurization schedules produced by mechanical valves for anti-G protection appear as linear functions of the acceleration. These are not optimized for Gz protection because the physiological responses to acceleration and the true pressure schedules delivered are nonlinear due to time delays and the reflex actions of the cardiovascular system. Fraser and colleagues (20) have developed models describing physiological responses to nonlinear, G-suit pressure and PBG schedules which will be used as aids in the development of new Gz-protection strategies. Microprocessor-based G valves and regulators were used to generate nonlinear pressure schedules. The blood-pressure responses at heart level to three pressure categories were obtained for:

- G-suit pressure without PBG;
- G-suit and PBG pressures controlled by a single valve, with PBG proportional to G-suit pressure; and
- G-suit and PBG pressures controlled by separate valves.

In some instances different ratios of G-suit to PBG pressures were applied to determine the point at which blood-pressure gain was maximized. The responses to step, ramp, pulse, sinusoidal and random inputs were determined. Based on the analysis completed, it would appear that a single-zero, double-pole model adequately describes blood-pressure response to G-suit pressure with and without PBG at +1Gz and, possibly, at higher Gz levels. Intersubject variations in response to G-suit pressures were common and intrasubject response variations were noted at different times during an experiment. These findings might impede the development of subject-specific Gz-protection strategies.

Fraser and colleagues (21) also tried a nontraditional systems-identification approach to model the cardiovascular response to nonlinear, anti-G-suit and PBG pressure schedules for both +Gz and push-pull transitions. The goal was to develop an expert system - a Physiological Data Analysis Toolbox - that would enable those with little experience in analysis to work through a set of experiments. At another level, the purpose of the work was to provide a method of analysis for the development of customized pressure schedules for anti-G pilot protection, in general, and for push-pull countermeasures, in particular. Recorded parameters were chosen as the heart-level arterial blood pressure, the electrocardiogram (ECG), the respiratory rate, and the G-suit and PBG pressures. The Toolbox integrated the results for these measures through statistical, trend, higher-order spectrum, and fuzzy-logic analyses of the data. Using this Toolbox, the correlation and trend dependencies established between the highly nonlinear pressure schedules and the physiological responses provided important information for screening data and the choice of method of analysis for modelling

protective systems in the high-G environment.

Rogers (22) described a model that focused on the dynamic response of the cardiovascular system to Gz, including the effect from the push-pull maneuvre. This model employed a second-order transfer function to account for the blood-pressure response to changes in Gz and G transition rates. It provided a descriptive picture of how the heart responds to the G environment, which should give some insight into strategies for improving G-LOC protection. By way of example, this model suggested that the choice of acceptable centrifuge profiles has not been optimized to describe the cardiovascular system most effectively under G conditions.

Burton (23) had earlier published a mathematical model based on hydrostatic principles that accurately predicted G-level tolerance with and without the use of G-protection methods such as the anti-G suit, PBG, and the anti-G straining maneuvre (isometric muscle contraction) (Aviat. Space Environ. Med. 57(8): 733, 1986). This model was validated and found to be extremely practical; it has been used by engineers in cockpit design for predicting G-level tolerance to various personal protective measures, and by lecturers in teaching high-G physiology. With the availability of further physiological data, the model has now been refined to include the ability to assess tolerances to G-duration (to account for the additional contributions of anaerobic capacity, muscular strength, and muscle blood flow to the evolution of G-induced fatigue), and to improve G-level assessments (by including venous return for predicting both blackout and G-LOC conditions). With these modifications, the effectiveness of protective systems up to 12 G can be predicted accurately. In conducting high-G research and testing, one is always concerned with the risk to the safety of the subject. Accordingly, good practical, validated models such as this one proposed by Burton will increasingly reduce the need for human volunteer participation in future G studies, and insure their safety when testing is required.

5.6 Modelling Human Responses to Other Adverse Flight Environments

Papers on promising models in mechanical shock, vibration, motion sickness and altitude decompression sickness (DCS) were also invited to this Specialists' Meeting.

Repeated mechanical shocks long have been associated with low back pain and degenerative disorders of the spine. Methods of evaluating mechanical-shock exposure have relied on signal-processing techniques rather than on human-response data or biomechanical analyses. Morrison and colleagues (24) described a new method, called the Health Hazard Assessment (HHA), for evaluating the effects of repeated mechanical shocks on the health of vehicle operators. The HHA model formulates the risk of operator injury (output) in terms of vehicle-seat acceleration (input). There are four stages that are combined to produce the HHA model:

- Dynamic response models are used to predict the three-dimensional accelerations of the lumbar spine as measured at the occupant seat.
- Lumbar compressive forces at the L4/5 vertebral joint to shock inputs at the seat are estimated from peak lumbar accelerations derived from a biomechanical analysis.
- A dose model based on fatigue-failure tissue properties, and the compressive strength of the L4/5 vertebral joint calculate the effect of repeated compressive loading.
- Injury risk is then determined from the accumulated compressive dose, the tissue fatigue life, the variance from the vertebral-joint-strength data, and the cumulative probability of failure.

The HHA model predicts the risk of injury from a single exposure or from the cumulative shock effects of a lifetime of repeated mechanical shocks. This new model has shown promising results; however, it will require further rigorous testing before it is generally accepted by safety experts.

Vehicular whole-body vibration has long been associated with health problems, performance degradation, discomfort, and fatigue. Smith (25) conducted a series of tests, using small females and large males, to collect sensor (biodynamic) data of critical human body parts to vertical vibrations. Responses obtained from the data, using the driving-point impedance and transmissibility techniques both of which are characterized by input/output response ratios as functions of frequency, were subsequently compared with responses obtained from a five degree-of-freedom, lumped-parameter model. This model simulated the resonance behaviour of the human body when it was positioned in a rigid seat with and without the benefit of seat cushions. The model was quite effective in simulating many of the rigid-seat responses, particularly for the male. In evaluating aircraft seat cushions, the model showed the benefits of using such cushions, and some of the differences in vibration response between the male and female. The study also demonstrated the need for additional modifications to the model, e.g., improved leg representation, possible inclusion of other body parts, better coupling of parts, etc.

The quest for a sound model that will predict motion-sickness incidence satisfactorily has long been a goal of aerospace scientists. Bos and Bles (26) have developed a motion-sickness model wherein the organs of balance

(vestibular organs) together with control-systems concepts play an essential role. There are three important aspects to the model:

- From multisensory input information, the brain resolves a so-called sensed vertical vector representing the magnitude and direction of the sensed acceleration of gravity.
- At the same time, the brain uses an optimal-estimation strategy to create a subjective (anticipated) vertical that is based on past experiences.
- Motion sickness occurs when there is a conflict between sensed and subjective verticals.

The current paper described the model when it is restricted to resolving inputs solely from the vestibular system, i.e., otolithic (gravity and linear-acceleration sensing) and semicircular canal (angular-acceleration sensing) inputs. The true vertical is resolved by the brain through low-pass filtering of otolithic information, and rotation information is provided by the semicircular canals. The model predicts that the incidence of motion sickness for pure vertical transitions is greatest at a frequency of 0.16 Hz, a value observed experimentally. The model is expected to be responsive to other inputs, e.g., visual, proprioceptive, and even cognitive information, and anticipated to accurately predict the incidence of sea, air, simulator and other analogous sicknesses. A comment from the audience inferred that there was, in fact, visual perception involved during the vertical transitions in the example cited by the authors that was inadvertently omitted in the analysis.

Decompression sickness is thought to occur from the formation and growth of bubbles resulting from dissolved, tissue nitrogen gas coming out of solution with a large and rapid reduction in environmental pressure. Weakness, numbness, pain, paralysis, and even death can occur with DCS. Typically though, the incidence of altitude DCS is in the range of 25 - 30%, symptoms are usually mild, and mostly limited to joint pain which is cleared on return to ground level. The most significant variables that influence the occurrence of DCS risk include the pressure and exposure time at altitude, the preoxygenation time, and the level of exercise undertaken. Taking these factors into account, Petropoulos, Kannan, and Pilmanis (27) have developed an Altitude DCS Risk Assessment (ADRAC) computer that determines on-site estimates of the risk of DCS in real time for altitudes from 18,000 to 40,000 feet (5.5 to 12.2 km). The computational algorithm in ADRAC is based on a multi-component gas-bubble growth model and survival-analysis techniques for predicting DCS risk. Altitude-exposure profiles tested with ADRAC were within +/-5% error of observed values taken from an AFRL data bank of over 2000 altitude exposures.

5.7 Modelling Human Responses to Harsh Conditions in Air Environments

The final set of papers at this Specialists' Meeting addressed issues on modelling human responses to harsh conditions that would apply to all military services, not just those in the aviation environment.

Neades, Klopcic, and Davis (28) described a new methodology for assessing the impact of battlefield trauma on performance of military tasks. The methodology employs an Operational Requirement-based Casualty Assessment (ORCA) model that determines the anti-personnel effects associated with various weapon-induced threats. The ORCA computer code enables calculation of the anatomical damage resulting from exposure to kinetic energy (fragments), thermal, chemical, directed energy (lasers), blast, and accelerative loading threats. The effect of a computed injury is characterized by the predicted impairment of each of 24 human elemental capabilities (e.g., vision, cognition, and physical strength). ORCA then determines the effect of such damage on individual task performance. Thus, post-injury CAPABILITY IMPAIRMENT is compared to CAPABILITY REQUIREMENT associated with the individual's military job, task, or mission to determine if (s)he is an OPERATIONAL CASUALTY. Code outputs for discrete exposures (e.g., single fragment) include a physical damage summary, details of any deleterious processes (e.g., blood loss), and an indication of the remaining performance capability (incapacitation) as a function of time following trauma (immediate, 30 seconds, 5 minutes, 1 hour, 24 hours, and 3 days). ORCA can produce results to both single and multiple exposure conditions.

Hurt and Mason (29) described models for determining the energy absorbed by the human body when exposed to radio-frequency directed energy (dosimetry models). Of particular importance is the Specific Absorption Rate (SAR) which is manifested as heat energy during directed energy exposure. This can be measured using whole-body calorimetric or other thermometric methods. Accurate SAR values and distributions for the full-sized human analog are now possible using such pertinent biological data together with iterative numerical methods, such as the finite-difference time-domain method, that require powerful computer processing capabilities. The ultimate goal of this work should be the establishment or updating of radio-frequency safety standards using combinations of anatomical and mathematical models that are based on noninvasive measurements and do not involve human-subject exposure.

Miller and Carver (30) discussed a sub-model of ORCA designed to predict the probability of ocular injury from laser insults. Sub-model input parameters included:

- laser type, wavelength, energy density, and insult duration;
- ocular injury assessment in regard to corneal damage/photokeratitis, flashblindness, and retinal damage;
- relevant body components, i.e., right and left eyes and retinas; and
- elemental capability degradation in regard to visual acuity (including colour vision), night vision, field of view, and binocular vision (including ocular motility).

Examples were given illustrating the applicability of the sub-model when integrated into the ORCA code.

Burns resulting from fires or other thermal sources represent a significant threat to aircrew safety. Models that predict burns are important because there is an increasing reluctance to use animals to assess burn trauma in humans. Moreover, burn preventive techniques such as the use of protective clothing and improved vehicle design require good models to accurately predict and assess burn injury. Two papers discussed the issue at this Specialists' Meeting.

Knox and colleagues (31) developed BURNSIM, an interactive model employing a heat-conduction equation, for predicting burns, that is based on the work of several earlier investigators including that of Henriques (Arch. Path. 43(5): 489, 1947). They indicated that BURNSIM, which is being incorporated into ORCA, predicts with reasonable accuracy the heat transferred through clothing when the initial conditions and thermal conditions are adequately defined. The model also has found utility in assessing burn hazards from rocket exhaust during side-by-side ejections, aerothermal heating during pilot ejection at supersonic speeds, aircraft fires, and other thermal threats.

Lawton and colleagues (32) presented a method for accurately predicting first-, second-, and third-degree skin burns from conductive, convective, and high- and low-temperature radiation sources. Subject to certain allowances, Henriques' original theory was sufficient to describe all of these skin burns. The computer model used to determine burn damage was based on a one-dimensional, transient, heat-conduction equation. Thermal data collected from fireballs produced by ignition of pyrotechnic compositions were evaluated by this model. This burn damage function related heat input (skin temperature or heat dose), for different burn depths, to the time during and after exposure to a heat source. BURNSIM provided similar information.

Blast overpressure on the body caused by explosives or weapon impulse noise can rapidly collapse human air-bearing organs causing injuries ranging from isolated pathologies with no physiological effects to those having more critical consequences involving organ rupture and death. The US Army Medical Research and Materiel Command uses lethality and injury data from animals to correlate with the pressure-duration characteristics of free-field blasts. However, these correlations become meaningless in a reverberant environment such as that experienced when weapons are fired in an enclosure, or a portion of the blast energy is deflected back to the individual firing the weapon. Stuhmiller et al. (33) have developed a thoracic-injury, finite-element model that provides a realistic biomechanical basis for thorax motion under reverberant conditions. Moreover, by choosing tissue material properties judiciously, the model effectively correlates calculated internal stresses resulting from such blast loading with observed lung injury. This work is being considered as a new exposure standard for lung injury.

6. CONCLUSIONS AND RECOMMENDATIONS

This meeting dealt with the modelling of human responses and human-systems interactions to a variety of hazardous conditions in air environments.

There have been significant advances made in modelling human physical and physiological responses to deleterious aircrew stresses, and in modelling the interaction of aircrew with the mechanical systems upon which hazardous conditions are imposed. To a great extent these advances are due to the following:

- the large collection of animal and volunteer human test data taken over the past 30 years of subcritical material properties of relevant biological tissues, and biomechanical responses,
- the significant collection of injury tolerance data extracted from accident reconstruction and analysis, and controlled animal and/or cadaver tests over the past 30 years,
- the development of sophisticated biodynamic test facilities, many of them man-rated, for collecting biodynamic response data,
- the development of a wide variety of sensors having improved frequency responses, some of which are highly miniaturized, for rapid and unencumbered data collection,
- the inordinate cost reductions and advances in computer speed and power for data acquisition, data analysis and model development,
- the wide variety of models developed, particularly the progress made in finite-element analysis, for analyzing and modelling human responses, and

- the corresponding evolution in the understanding and modelling of the aerodynamic effects of normal and hazardous flight conditions affecting human-systems interactions.

Because of the extensive developments made in designing appropriate, validated, human biodynamic models, the requirement for the collection of animal and volunteer human test data will likely be reduced in the future.

Notwithstanding the important advances made in model development, many realistic representations of human physiology and cognition under different aviation stresses in simulated environments are still missing and will require more human and animal testing. Some examples may be cited in support of this position:

- Validated models of the non-linear dynamic stresses and strains of muscles, brain and other biological tissues during impact are missing. These could contribute substantially to the development of more reliable injury criteria, thereby enabling improved crashworthiness designs to be developed. Similarly, as demonstrated by Lawton, Knox, Hurt, Miller and their colleagues at this meeting (29 - 32), the highly nonlinear nature of extreme thermal conditions and directed energy make it difficult to develop predictive models of human-interaction phenomena.
- Although the behaviour of the cardiovascular and cerebrovascular systems, and the dynamics of anti-G protective hardware to sustained acceleration have been modelled quite effectively, as Fraser and his colleagues have demonstrated at this meeting (14 - 16), the integrative nature of these human-systems interactions is severely lacking though essential to adequately address design issues.

There is much hope that with increasing computer speed and power, finite-element analysis will progress significantly and become more prevalent in modelling human-systems interactions. Finite-element modelling has been used to model stresses and deformations in realistic ways; however, more exacting biomaterial properties must be obtained before this method can be fully exploited. The use of finite-element analysis, coupled with rigid-body modelling, has shown great promise in analyzing human dynamics under the loading conditions of crash and ejection accelerations. As exemplified during this meeting, the MADYMO computer program (6, 13), developed by TNO Road-Vehicles Research Institute in The Netherlands, effectively combines both finite-element and rigid-body (multi-body) structures to allow simultaneous simulation of gross body motion and deformation.

Computer models of the airframe, the cockpit including the ejection seat, and other critical aircraft subsystems are increasingly being used by decision-makers to reconc design aims and to cut design costs in the procureme process. It is important that aircrew safety models be integral part of this process. Moreover, such subsyste safety models employing validated biodynamic data ba will have to interoperate with these other aircr subsystem models effectively if safe design conditions a to be optimized in a virtual prototype environment. T experiences of Ma and colleagues (9) in their presentati on evaluating ejection-seat/crew interaction are an exam of such a simulation. Using the ATB model, developed the AFRL/WPAFB, in combination with wind-tunnel t data, Ma and colleagues successfully demonstrated the k features of seat motion and crew-member responses duri critical seat operation stages in ejection.

In the future, simulation within NATO defer organizations will combine models and analytical to (i.e., constructive simulations) with pilot-in-the-lo synthetic environments (i.e., virtual simulations) that m or may not involve motion-based features. On t constructive side, scenario generators will provide t physical environment necessary to characterize aircr flight maneuvres and threat conditions, and provide t conditions necessary for addressing and resolving criti human factors and human protection countermeasures. (the virtual side, by immersing the human in the synthe environment, real safety systems and human performar may be assessed as to function, fit, capability, etc. Playi back and forth between constructive and virt simulations should enable various options to be assess and provide the performance tradeoffs required improving safety system features, thereby reducing t need for subsequent live test requirements.

Inevitably, all NATO air forces will depend constructive simulations for planning functions such concept development, design, test and evaluation, a mission rehearsal. All of these functions impact on aircr safety. However, current scenario generators representi automated personnel conducting operations in constructi simulations do not adequately depict human attributes a the human reactions in dealing with different comb stressors. Modelling the effects of fatigue, worklo combat injuries and other stressors on decision making constructive simulations in a way that is usable by plann is a difficult though important challenge that should not unheeded by model builders. Furthermore, such mod should be time dependent in order that human performar deterioration with continuing stress is taken into accou Moreover, individual differences in the physiological a psychological composition of aircrew must also be component of such models if aircrew safety is not to compromised.

Because of the advancements made in digital nnologies, simulation environments in the near future, ploying either or both constructive and virtual ulations, will communicate over local- or wide-area works. These systems will allow dissimilar models from .TO and other worldwide research and industrial ations to interact with each other on various data bases form common simulations. This will facilitate the persion and use of aircrew safety models in design and processes, but it will also require greater ndardization of digital data recording systems and data es to exchange data sources. Maintaining good model l data base validation and verification procedures will e on added importance.

Advances in simulation and distributed interactive working provide opportunities for increased laboration among NATO scientists and engineers rking in widely different fields and locations to reach mmon goals in model and data base developments. Such abases and any analogous pre-competitive modelling hniques, tools and ideas developed should be generally ilable to all, and conform to accepted procedures of ndardization, validation, and verification. An example such a collaborative effort might include the setting up data bases of trauma injuries and the development of nbat-casualty submodels that port into models such as ORCA software described at this meeting by Neades l colleagues (28).

As indicated earlier, Dr von Gierke, at a symposium in '7, spoke to the need for a national biodynamics data nk that would store the essential material properties and chanical characteristics for model development. This a bank would have been centralized, and fed into and red by all laboratories working in the field. Perhaps, h the increased emphasis on simulation and modelling the design process and the requirement for greater ional and international collaboration, it is time to end Dr von Gierke's proposal and strive for a series of rnational biodynamics and trauma-injury data bases hin NATO defence research laboratories.

These data bases would capture the relevant data ilable in the different aircrew environments, e.g., data lected on impact/ejection/sustained accelerations, ade, etc. in the different countries, and these would be dily available to all NATO nations conducting laborative research and design. In particular, data from ious hazardous human experiments should be included hese data bases before these are lost, or rendered useless ough aging recording media (film, paper, etc.) or ause of incompatibilities between new versus old data der systems. It is unlikely that such data will ever be ted again because of the stringent (though necessary) itational requirements now being mandated to protect human subjects during experimentation. Perhaps the HFM Panel of the NATO/RTO could take the lead in assessing the feasibility of establishing such a series of databases. Perhaps also, the HFM Panel could take the initiative in developing a strategy for a better sharing of pre-competitive modelling techniques, tools and ideas for aircrew safety.

7. ACKNOWLEDGEMENTS

We thank Mrs N. Wisteard for preparation of this manuscript and general administrative assistance.

DCIEM No. SL 1999-012